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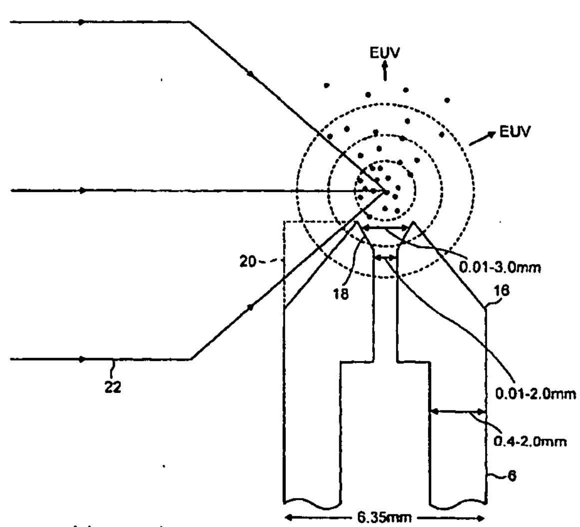
(54) Title: ELECTROMAGNETIC RADIATION GENERATION USING A LASER PRODUCED PLASMA



(57) Abstract: An extreme ultraviolet radiation generator (2) is provided in which Xenon gas is continuously ejected from a high pressure nozzle (6) into a low pressure chamber (8) to generate Xenon atom clusters which are irradiated with a high repetition rate pulsed laser to form a plasma and yield quasi-continuous EUV generation. The nozzle (6) has a bevelled outer rim (12) to enable the focus point of the laser light to be brought close to the nozzle (6). The nozzle (6) is cooled to a temperature at which background Xenon gas condenses onto the nozzle forming a protective layer (28). A gas compressor (30) serves to recirculate the Xenon gas and batch purification triggered by a mass spectrometer (32) monitoring gas purity may be periodically applied.

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ELECTROMAGNETIC RADIATION GENERATION USING A LASER PRODUCED PLASMA

This invention relates to the field of the production of electromagnetic radiation from a laser produced plasma. More particularly, this invention relates to the generation of electromagnetic radiation, such as extreme ultraviolet radiation, using a plasma produced by directing laser light onto target matter produced by expelling a gas at high pressure from a nozzle.

Lasers may have peak power outputs as high as many terawatts (10^{12} W) and when this energy is tightly focused onto a solid or into a gas, the material is rapidly heated and ionised to form a plasma. Materials at kilo-electron-volt temperatures are in the plasma state. During laser production of a plasma, the plasma will typically be heated to kilo-electron-volt temperatures and the surface plasma will ablate, i.e. expand freely into the surrounding vacuum at its sound speed, exerting a very high thermal pressure of up to 10^{11} Pascal. As the plasma ablates it expands and cools adiabatically. As it cools recombination of the ionised plasma occurs and electrons cascade down through the atomic states resulting in emission of high energy radiation (such as extreme ultraviolet (EUV)) as the electrons decay to their lower energy states. The duration of the laser pulse may vary from several nanoseconds down to about 10 femtoseconds depending on the application and the method of production.

The generation of EUV radiation is useful in the fields of materials science, microscopy and micro-lithography amongst others. Currently integrated circuits are formed by a process using deep UV light which has a wavelength of about 308 or 248 or 193 x 10^{-9}m which can be used to create integrated circuit features down to below 250 x 10^{-9}m in width (limited by diffraction effects). It has been proposed that EUV radiation which has a wavelength of 10-15 nm, could be used to etch smaller integrated circuit features desirable for improved integrated circuit performance. Thus, the reliable production of high intensity EUV radiation is an important goal.

As explained above, one method of producing EUV radiation is to direct powerful lasers on a target material of high atomic mass and high atomic number. In order to produce a plasma, the target material must have an electron density which exceeds a critical density. Solid metal targets can be used when irradiated by high intensity pulsed lasers to produce a plasma above the target surface. However, the high pressure exerted back onto the target by the expanding plasma results in the production of high velocity particulate ejecta which can damage the optics of the nearby laser EUV optical collection systems. Even small amounts of debris can do considerable damage, e.g. by dramatically reducing the reflectance of mirrors.

One way of reducing the plasma's particulate ejecta is to use a target source of atomic molecular clusters. Inert noble gases such as Xenon are typically used. The molecular cluster targets are produced by free-jet expansion of a gas through a nozzle. The gas is fed into the nozzle inlet at high pressure and is ejected at force through a nozzle outlet into a low pressure chamber. The gas undergoes isentropic expansion in the low pressure chamber which results in cooling. Clusters form when the gas temperature drops sufficiently so that the thermal motion of the Xenon atoms cannot overcome the weakly attractive Van der Waals forces between the atoms. The precise geometry of the nozzle determines important properties of the source jet such as the density and degree of clustering, and in turn these properties determine the intensity of the emitted EUV radiation. Each gas cluster may be thought to act like a microscopic solid particle target for laser plasma generation

A discussion of EUV generating systems of the above general type may be found in United States Patent US-A-5,577,092 and United States Patent US-A-6,011,267.

Viewed from one aspect the present invention provides apparatus for generating electromagnetic radiation at or below ultraviolet wavelengths, said apparatus comprising:

a low pressure chamber;

a nozzle projecting into said low pressure chamber and operable to pass a continuous flow of a fluid at high pressure into said low pressure chamber, said fluid being subject to cooling through expansion to yield matter suitable for use as a laser target and gas;

one or more optical elements operable to direct laser light on to said matter to generate a plasma emitting electromagnetic radiation at or below ultra-violet wavelengths; and a fluid recirculation apparatus for generating electromagnetic radiation at or below ultraviolet wavelengths, said apparatus comprising:

a low pressure chamber;

a nozzle projecting into said low pressure chamber and operable to pass a continuous flow of a fluid at high pressure into said low pressure chamber, said fluid being subject to cooling through expansion to yield matter suitable for use as a laser target and gas;

one or more optical elements operable to direct laser light on to said matter to generate a plasma emitting electromagnetic radiation at or below ultra-violet wavelengths; and

a fluid recirculation circuit for recirculating fluid from the low pressure chamber back to the nozzle including a purification unit for purifying the fluid.

Preferably the fluid recirculation circuit comprises a gas pumping system comprising at least a series connected connector of at least one blower pump together with another pump operable to evacuate from said low pressure chamber.

The production of high intensity ultraviolet and below light is strongly desirable and is aided by the use of a continuous flow of fluid through the nozzle rather than the more typical pulsed flow. It is normally regarded that continuous flow would not be practical due to the high pumping requirements necessary to keep the pressure within the low pressure chamber from building to too high a level. However, an embodiment of the invention uses a series connected blower pump and piston pump to evacuate up to 30 litres per minute of standard pressure gas from the low

pressure chamber and it has been found that this combined with continuous flow produces a working system capable of high intensity output (including EUV).

The gas pumping system is further improved in embodiments in which there is provided a series connection of one or more blower pumps together with a rotary pump and/or a piston pump. Each blower pump is preferably a Roots blower.

With the continuous flow of gas into the low pressure chamber, this may be advantageously subject to high repetition rate laser pulses to generate the plasma using pulses of between 1 and 100 kHz and more preferably between 2 and 20 kHz. This gives a quasi-continuous EUV source.

With such continuous operation, the high volumes of gas consumed would normally represent a significant economic barrier. However, recirculating the gas through a compressor enables such continuous operation to become a more practical consideration.

With such recirculation, preferred embodiments also provide a purification unit, which may be triggered by a mass spectrometer used to monitor gas purity, that serves to batch purify the gas as required.

It will be appreciated that the high pressure fluid passing through the nozzle could be in a liquid or fluid state prior to expansion into the low pressure chamber. However, preferred operation is achieved when the fluid is a gas. A particularly suitable gas is Xenon gas.

Whilst the wavelength of the radiation produced could vary depending upon the nature of the plasma produced, which in turn will be influenced by the nature of the gas and the laser light, the present invention is particularly well suited to the generation of extreme ultraviolet light.

The electromagnetic radiation produced by the systems of the present invention may be useful in a wide range of applications, but is particularly well suited as a radiation source for use within an integrated circuit lithography system.

Viewed from another aspect the present invention provides a method of generating electromagnetic radiation at or below ultraviolet wavelengths, said method comprising the steps of:

passing a fluid at high pressure into a low pressure chamber through a nozzle, said fluid being subject to cooling through expansion to yield matter suitable for use as a laser target and gas;

focusing laser light on to said matter to generate a plasma emitting electromagnetic radiation at or below ultra-violet wavelengths;

recirculating said fluid from the lower pressure chamber to the nozzle via a recirculation circuit including a purification unit; and

purifying said gas in said purification unit.

Viewed from another aspect the present invention provides apparatus for generating electromagnetic radiation at or below ultraviolet wavelengths, said apparatus comprising:

a low pressure chamber;

a nozzle projecting into said low pressure chamber and operable to pass a fluid at high pressure into said low pressure chamber, said fluid being subject to cooling through expansion to yield matter suitable for use as a laser target and gas;

one or more optical elements operable to direct laser light on to said matter to generate a plasma emitting electromagnetic radiation at or below ultra-violet wavelengths; and

a nozzle temperature controller operable to maintain said nozzle at a temperature at which said gas within said low pressure chamber condenses upon said nozzle and serves to protect said nozzle from said plasma.

The invention recognises that the gas expelled from the nozzle can itself be used to protect the nozzle from erosion and damage by the plasma being generated. In particular, maintaining the temperature of the nozzle at a level where the background gas within the low pressure chamber condenses onto the nozzle forms a protective layer of condensed gas on the nozzle that resists the damage produced by the plasma.

Whilst the range of temperatures at which the nozzle must be maintained to achieve such gas condensation can vary, in preferred embodiments the nozzle is maintained at a temperature of between 70 and 200 Kelvin.

The temperature controller can employ various mechanisms for cooling the nozzle, but preferred techniques found to operate effectively utilise pumped liquid nitrogen to cool the nozzle and resistive wire or lamp heaters to heat the nozzle as necessary.

Viewed from a further aspect the present invention provides apparatus for generating electromagnetic radiation at or below ultraviolet wavelengths, said apparatus comprising:

a low pressure chamber;

a nozzle projecting into said low pressure chamber and operable to pass a fluid at high pressure from a nozzle outlet into said low pressure chamber, said fluid being subject to cooling through expansion to yield matter suitable for use as a laser target; and

one or more optical elements operable to focus laser light on to said matter to generate a plasma emitting electromagnetic radiation at or below ultra-violet wavelengths; wherein

said nozzle has a bevelled outer rim portion and said one or more optical elements are disposed to focus said laser light onto said matter along a converging path which would be at least partially blocked by an outer rim flush with said nozzle

outlet at an outer diameter of said nozzle that would be present if said nozzle did not have said bevelled outer rim portion.

The invention recognises that a significant increase in the intensity of the electromagnetic radiation generated can be achieved by focussing the laser light close to the nozzle outlet where the number density of the target matter clusters is higher. The invention also recognises that in doing this the geometry of the nozzle needs to be adapted such that the converging laser light is not blocked by the outer rim of the nozzle. In this way, the intensity of the electromagnetic radiation can be increased whilst maintaining a large cone angle. A further advantage that may result is that the bevelled rim of the nozzle may be less subject to damage from the plasma as it is at a generally more acute angle to the plasma.

Reducing nozzle erosion reduces the likelihood of debris reaching the optical elements and contaminating them.

It will be appreciated that whilst the bevelled outer rim portion need only be provided upon the side of the nozzle from which the laser light is incident, the manufacturing of the nozzle may be simplified and the advantages of increased erosion resistance extended if the bevelled outer rim extends around the complete nozzle.

It will be appreciated that the outer wall of the nozzle could have many different cross sections. As an example, the outer wall of the nozzle could have a square cross section with one edge of the outer rim being bevelled to avoid interfering with the incident laser light. However, in preferred embodiments of the invention the outer wall of the nozzle has a circular cross section as this generally eases manufacturing and provides the required strength to the nozzle whilst not providing a nozzle that is too big as a subject for plasma erosion and contamination generation.

Whilst the bevelled outer rim portion can have various different profiles providing they avoid interfering with the incident laser light, a preferred profile is flat in that this is convenient to manufacture, provides good strength and can yield a constant acute angle between the outer rim bevelled face and the potentially damaging plasma. In the preferred embodiment the bevelled rim terminates at an acute angle reducing the surface area of the nozzle end and hence the area most exposed to debris.

Whilst the relative dispositions of the optical elements and the nozzle with its bevelled outer rim portion could have many combinations, it is preferred that the bevelled outer rim portion is sloped at an angle greater than the angle of convergence of the laser light. This allows a considerable degree of flexibility of the way in which the nozzle may be positioned relative to the laser light without the nozzle blocking the laser light. The provision of a bevel also provides robustness/structural strength and reduced occlusion of the radiation source.

The expansion of gas from the nozzle and the resistance to erosion of the nozzle may be further improved when the nozzle has a bevelled inner rim surrounding the nozzle outlet.

Whilst the nozzle could have various dimensions, it has been found that particularly good results are achieved when the nozzle outlet has a diameter of between 0.00001m and 0.002m. When the nozzle has a bevelled inner rim, then the diameter of the outer end of the opening may preferably be increased up to 0.003m. The nozzle walls preferably have a thickness of between 0.0004m and 0.002m.

In preferred embodiments of the invention the nozzle is mounted on a translation stage. This allows the nozzle to be accurately positioned relative to the optics to bring the focus point of the laser light accurately to a position close to the outlet of the nozzle thereby increasing the electromagnetic radiation generation intensity whilst avoiding the nozzle blocking the incident laser light.

In another form the invention provides an apparatus for generating electromagnetic radiation comprising a nozzle arranged to expel target matter and a laser arranged to direct laser light onto the target matter, in which the nozzle has a bevelled end.

In another form the invention provides apparatus for generating electromagnetic radiation comprising a nozzle arranged to expel target matter, a laser arranged to direct laser light onto the target matter, a detector for detecting a focal point of the laser light and a controller, in which at least one of the nozzle and laser are mounted on a translation stage and the controller is arranged to move the translation stage dependent on the detected focal point.

An embodiment of the invention will now be described, by way of example only, with reference to the accompanying drawings in which:

Figure 1 schematically illustrates an apparatus for generating extreme ultraviolet light;

Figure 2 schematically illustrates the geometry of a nozzle within the apparatus of Figure 1;

Figure 3 schematically illustrates the condensation of Xenon gas onto the nozzle within the apparatus of Figure 1; and

Figure 4 schematically illustrates a gas handling system for use with the apparatus of Figure 1.

Figure 1 shows an apparatus 2 for generating extreme ultraviolet light. This apparatus 2 operates by directing a flow of high pressure Xenon gas (for example at a

pressure of 10 to 70 bar) from a Xenon gas source 4 through a nozzle 6 and into the interior of a low pressure chamber 8. As the Xenon gas emerges from the nozzle 6 it is cooled to an extent whereby matter suitable for use as a target for generating a plasma is formed. This matter may be in the form of clusters of Xenon atoms. A high power stream of high repetition rate laser pulses from a single or multiplexed lasers is focused onto the Xenon atom clusters. The repetition rate is preferably between 1 and 100 kHz, more preferably between 2 and 20 kHz and achieved in single or multiplex configuration. This heats the Xenon atom clusters to a degree where a plasma forms, this plasma then emitting extreme ultraviolet radiation. Collection optics 10 serve to gather this extreme ultraviolet radiation for use within other systems, such as an integrated circuit lithography system. The optics 10 may comprise a mirror or mirrors.

The nozzle 6 is mounted upon a translation stage 12 which allows the nozzle to be accurately positioned close to the focus point of the laser light such that the laser light is focused where the number density of Xenon clusters is high. A photodiode (or other detector) can be provided to detect the focal point and allow automatic or closed loop control of the translation stage position in combination with a controller such as a microprocessor. The nozzle 6 is also cooled by a temperature controller 14 to a temperature at which the background Xenon gas within the low pressure chamber 8 condenses upon the surface of the nozzle 6. The flow of gas through the nozzle 6 is continuous at a rate of up to 30 standard litres per minute. A vacuum pump system connected to the low pressure chamber 8 servers to evacuate the low pressure chamber 8 to remove the Xenon gas continuously flowing into the low pressure chamber 8.

Figure 2 schematically illustrates the nozzle 6 in more detail. As shown, the nozzle 6 has an outer bevelled rim 16 and an inner bevelled rim 18. The dotted line 20 shows where the outer rim of the nozzle 6 would lie if the outer rim were not bevelled. More particularly, the outer surface of the nozzle 6 would extend flush with the outlet of the nozzle to a point bounded by the outer radial diameter of the nozzle 6. Such an

outer rim would block a significant portion of the incident laser light 22 used to generate the plasma.

As shown in Figure 2, the number density of the Xenon atom clusters close to the nozzle 6 is high and accordingly it is desirable to focus the laser light close to the nozzle outlet. However, the geometry of the nozzle and laser light focusing optics is such that a bevelled outer rim 16 is provided to avoid the nozzle 6 obstructing the incident laser light. It will also be seen that the bevelled outer rim 16 and the bevelled inner rim 18 are at a comparatively acute angle to the plasma and accordingly may suffer less damage from the plasma ejecta.

Thus, the nozzle 6 with the bevelled outer rim 16 enables the focus point of the laser light to be brought close to the nozzle outlet without the nozzle obstructing the laser light, even in the laser where there are multiple lasers. That provides less nozzle erosion and hence debris which may reach, and contaminate, the collection optics 10.

The nozzle 6 is conveniently manufactured in a form having a circular cross section using turning techniques. The outer bevelled rim 16 has a flat profile and extends around the complete circumference of the nozzle 6. Possible ranges for dimensions of different portions of the nozzle 6 are illustrated in Figure 2.

Figure 3 schematically illustrates how the nozzle 6 may be subject to temperature control. The temperature controller 14 uses a combination of liquid nitrogen pumped along tubes 24 close to the nozzle 6 and resistive wire or lamp heaters 26 close to the nozzle 6 to control the temperature of the nozzle 6 to be at a level at which the background Xenon gas within the low pressure chamber 8 condenses onto the outer surface of the nozzle 6. This condensed Xenon gas may be liquid or may be frozen. In either case, the layer 28 of condensed Xenon on the surface of the nozzle 6 provides a degree of protection to the nozzle 6 from erosion by

the plasma. The temperature controller 14 may control the temperature of the nozzle 6 to lie within the range of 70 to 200 Kelvin.

Figure 4 illustrates a gas system for use with the EUV generator 2 of Figure 1. A recirculating gas system is used in which series connected blower, rotary and piston pumps serve to continuously evacuate the low pressure chamber 8. The pump set includes Roots blower pumps, rotary pumps and a four stage piston/cylinder pump amongst other elements. This combination serves to provide the capacity to evacuate the low pressure chamber 8 keeping pace with the continuous flow rate of 2 to 30 standard litres per minute of Xenon into the low pressure chamber 8 through the nozzle 6.

A gas compressor 30 recompresses the Xenon gas evacuated from the low pressure chamber 8 up to the pressure of between 10 and 70 bar at which it is fed back to the nozzle 6. This continuous recirculation of the Xenon gas is practically significant as Xenon gas is an expensive raw material and the continuous operation of the apparatus 2 would be economically compromised if the Xenon gas were not recirculated. A mass spectrometer 32 or residual gas analysis (RGA) sensor serves to continuously monitor the purity of the Xenon gas flowing through the gas system and when this purity falls below a threshold level initiates purification of at least a portion of the Xenon gas using a batch purifier 34.

CLAIMS

1. Apparatus for generating electromagnetic radiation at or below ultraviolet wavelengths, said apparatus comprising:

a low pressure chamber;

a nozzle projecting into said low pressure chamber and operable to pass a fluid at high pressure from a nozzle outlet into said low pressure chamber, said fluid being subject to cooling through expansion to yield matter suitable for use as a laser target; and

one or more optical elements operable to focus laser light on to said matter to generate a plasma emitting electromagnetic radiation at or below ultra-violet wavelengths; wherein

said nozzle has a bevelled outer rim portion and said one or more optical elements are disposed to focus said laser light onto said matter along a converging path which would be at least partially blocked by an outer rim flush with said nozzle outlet at an outer diameter of said nozzle that would be present if said nozzle did not have said bevelled outer rim portion.

2. Apparatus as claimed in claim 1, wherein an outer wall of said bevelled outer rim portion forms a complete bevelled outer rim to said nozzle.

3. Apparatus as claimed in any one of claims 1 and 2, wherein said nozzle has a circular cross-section.

4. Apparatus as claimed in any one of the preceding claims, wherein said bevelled outer rim portion has a flat profile.

5. Apparatus as claimed in any one of the preceding claims, wherein said bevelled outer rim portion is sloped at an angle greater than an angle of convergence of said laser light.

6. Apparatus as claimed in any one of the preceding claims, wherein said nozzle has a bevelled inner rim surrounding said nozzle outlet.

7. Apparatus as claimed in any one of the preceding claims, wherein said nozzle outlet has a diameter of between 0.00001m and 0.002m.

8. Apparatus as claimed in claim 6, wherein said bevelled inner rim shapes said nozzle outlet to have a diameter at an outer end opening into said low pressure chamber of between 0.00001 and 0.003m and a diameter and an inner end remote from said low pressure chamber of between 0.00001m and 0.002m, said diameter at said outer end being greater than said diameter at said inner end.

9. Apparatus as claimed in any one of the preceding claims, wherein said nozzle has a wall thickness of between 0.0004m and 0.002m.

10. Apparatus as claimed in any one of the preceding claims, wherein said fluid is a gas.

11. Apparatus as claimed in any one of the preceding claims, wherein said fluid is XenonXenon gas.

12. Apparatus as claimed in any one of the preceding claims, wherein said electromagnetic radiation is extreme ultraviolet light.

13. Apparatus as claimed in any one of the preceding claims, wherein said apparatus is part of integrated circuit lithography system.

14. Apparatus as claimed in any one of the preceding claims, wherein said nozzle is mounted on a translation stage to allow for said nozzle to be moved relative to said

one or more optical elements to adjust a focus point of said laser light to be incident upon said matter.

15. Apparatus as claimed in claim 14 further comprising a detector arranged to detect the laser focus point and a controller arranged to control movement of the translation stage dependent on the detected focus point.

16. Apparatus for generating electromagnetic radiation comprising a nozzle arranged to expel target matter and a laser arranged to direct laser light onto the target matter, in which the nozzle has a bevelled end.

17. Apparatus for generating electromagnetic radiation comprising a nozzle arranged to expel target matter, a laser arranged to direct laser light onto the target matter, a detector for detecting a focal point of the laser light and a controller, in which at least one of the nozzle and laser are mounted on a translation stage and the controller is arranged to move the translation stage dependent on the detected focal point.

18. Apparatus for generating electromagnetic radiation at or below ultraviolet wavelengths, said apparatus comprising:

a low pressure chamber;

a nozzle projecting into said low pressure chamber and operable to pass a continuous flow of a fluid at high pressure into said low pressure chamber, said fluid being subject to cooling through expansion to yield matter suitable for use as a laser target and gas;

one or more optical elements operable to direct laser light on to said matter to generate a plasma emitting electromagnetic radiation at or below ultra-violet wavelengths; and

a fluid recirculation circuit for recirculating fluid from the low pressure chamber back to the nozzle, including a purification unit for purifying the fluid.

19. An apparatus as claimed in claim 18 in which the fluid recirculation circuit comprises a gas pumping system comprising at least a series connection of at least one blower pump and another pump operable to evacuate from said low pressure chamber per minute at least an amount of said gas that would occupy 30 litres at atmospheric pressure.

20. Apparatus as claimed in claim 19, wherein said gas pumping system comprises at least a series connected blower pump, rotary pump and piston pump.

21. Apparatus as claimed in claims 19 or 20, wherein said gas pumping system further comprises a compressor operable to compress said gas to form said fluid that passes through said nozzle.

22. Apparatus as claimed in claim 21, further comprising a purification unit for batch purifying said gas.

23. Apparatus as claimed in any one of claims 21 and 22, wherein gas purity is monitored by a mass spectrometer to detect if gas purity has fallen below a threshold level.

24. Apparatus as claimed in claims 22 and 23, wherein said purification unit is triggered to purify said gas when gas purity falls below said threshold level.

25. Apparatus as claimed in any one of claims 18 to 24, wherein said fluid is a gas.

26. Apparatus as claimed in claim 25, wherein said fluid is Xenon gas.

27. Apparatus as claimed in any one of claims 18 to 26, wherein said electromagnetic radiation is extreme ultraviolet light.

28. Apparatus as claimed in any one of claims 18 to 27, wherein said apparatus is part of a semiconductor lithography system.

29. Apparatus as claimed in any of claims 18 to 28, comprising a pulsed laser source or sources having a repetition of between 1kHz and 100kHz more preferably 2 to 20kHz as a source of said laser light.

30. A method of generating electromagnetic radiation at or below ultraviolet wavelengths, said method comprising the steps of:

passing a fluid at high pressure into a low pressure chamber through a nozzle, said fluid being subject to cooling through expansion to yield matter suitable for use as a laser target and gas;

focusing laser light on to said matter to generate a plasma emitting electromagnetic radiation at or below ultra-violet wavelengths;

recirculating said fluid from the low pressure chamber to the nozzle via a recirculation circuit including a purification unit; and

purifying said gas in said purification unit.

31. Apparatus for generating electromagnetic radiation at or below ultraviolet wavelengths, said apparatus comprising:

a low pressure chamber;

a nozzle projecting into said low pressure chamber and operable to pass a fluid at high pressure into said low pressure chamber, said fluid being subject to cooling through expansion to yield matter suitable for use as a laser target and gas;

one or more optical elements operable to direct laser light on to said matter to generate a plasma emitting electromagnetic radiation at or below ultra-violet wavelengths; and

a nozzle temperature controller operable to maintain said nozzle at a temperature at which said gas within said low pressure chamber condenses upon said nozzle and serves to protect said nozzle from said plasma.

32. Apparatus as claimed in claim 31, wherein said nozzle temperature controller maintains said nozzle at a temperature of between 70K and 200K.

33. Apparatus as claimed in claims 31 or 32, wherein said nozzle temperature controller uses pumped liquid nitrogen to cool said nozzle.

34. Apparatus as claimed in any one of claims 31 to 33, wherein said nozzle temperature controller uses at least one of a resistive wire heater and a lamp heater to heat said nozzle.

35. Apparatus as claimed in any one of claims 31 to 34, wherein said fluid is a gas.

36. Apparatus as claimed in any one of claims 31 to 35, wherein said fluid is Xenon gas.

37. Apparatus as claimed in any one claims 31 to 36, wherein said electromagnetic radiation is extreme ultraviolet light.

38. Apparatus as claimed in any one of claims 31 to 37, wherein said apparatus is part of a semiconductor lithography system.

39. A method of generating electromagnetic radiation at or below ultraviolet wavelengths, said method comprising the steps of:

passing a fluid at high pressure into a low pressure chamber through a nozzle, said fluid being subject to cooling through expansion to yield matter suitable for use as a laser target and gas;

directing laser light on to said matter to generate a plasma emitting electromagnetic radiation at or below ultra-violet wavelengths; and

maintaining said nozzle at a temperature at which said gas within said low pressure chamber condenses upon said nozzle and serves to protect said nozzle from said plasma.

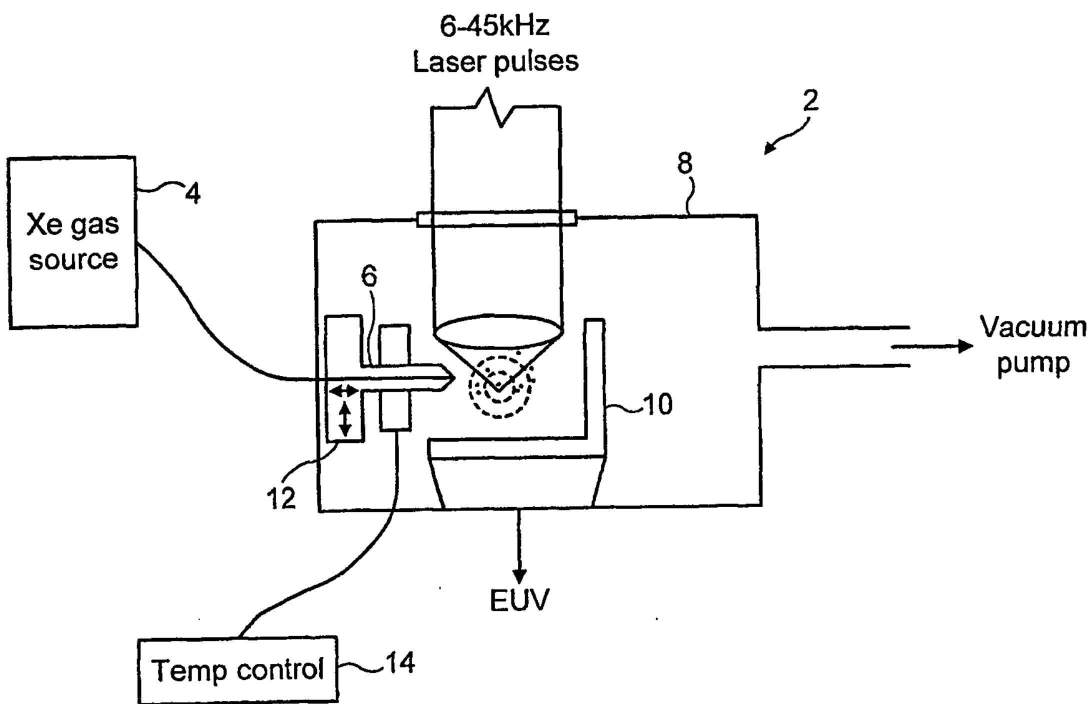

FIG. 1

SUBSTITUTE SHEET (RULE 26)

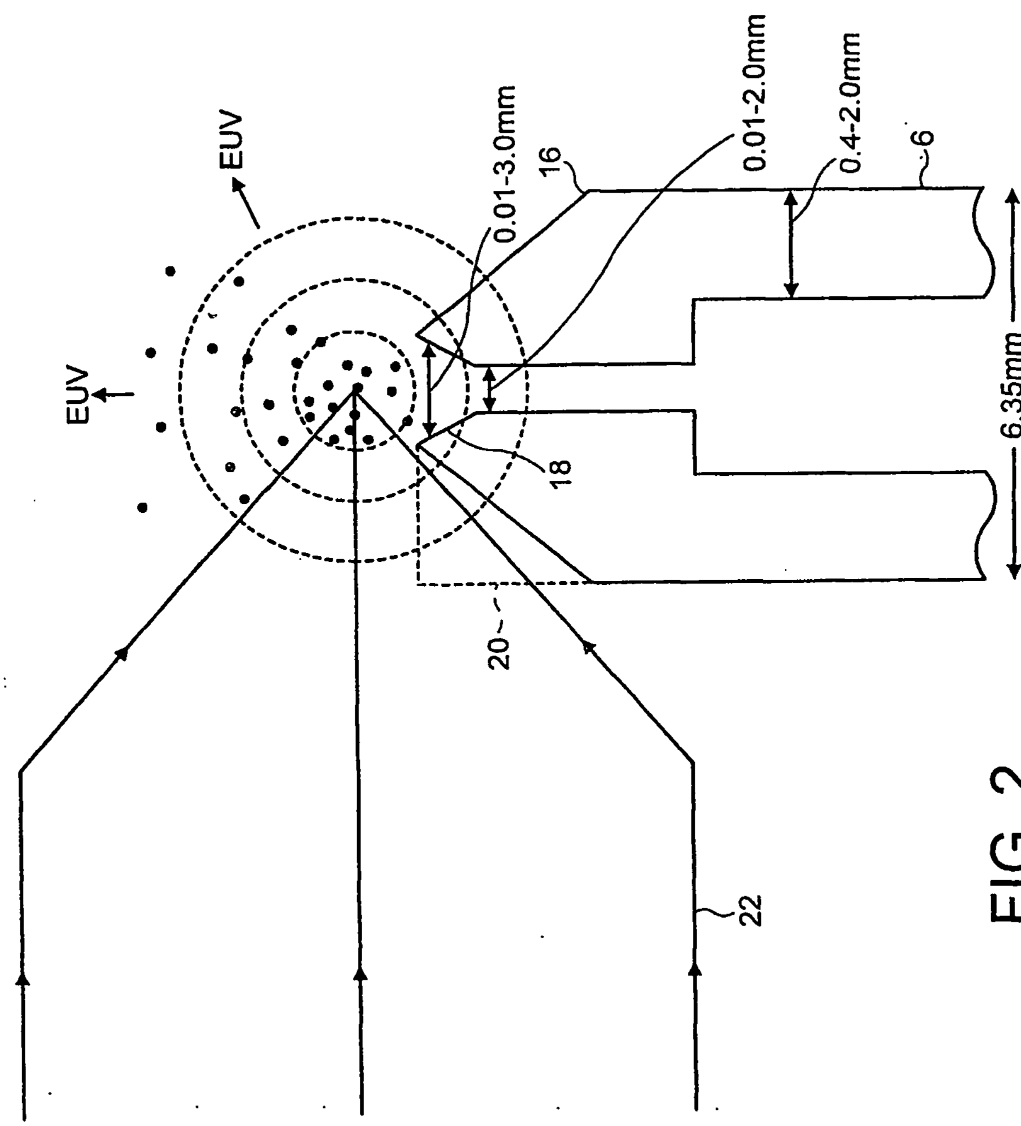

FIG. 2

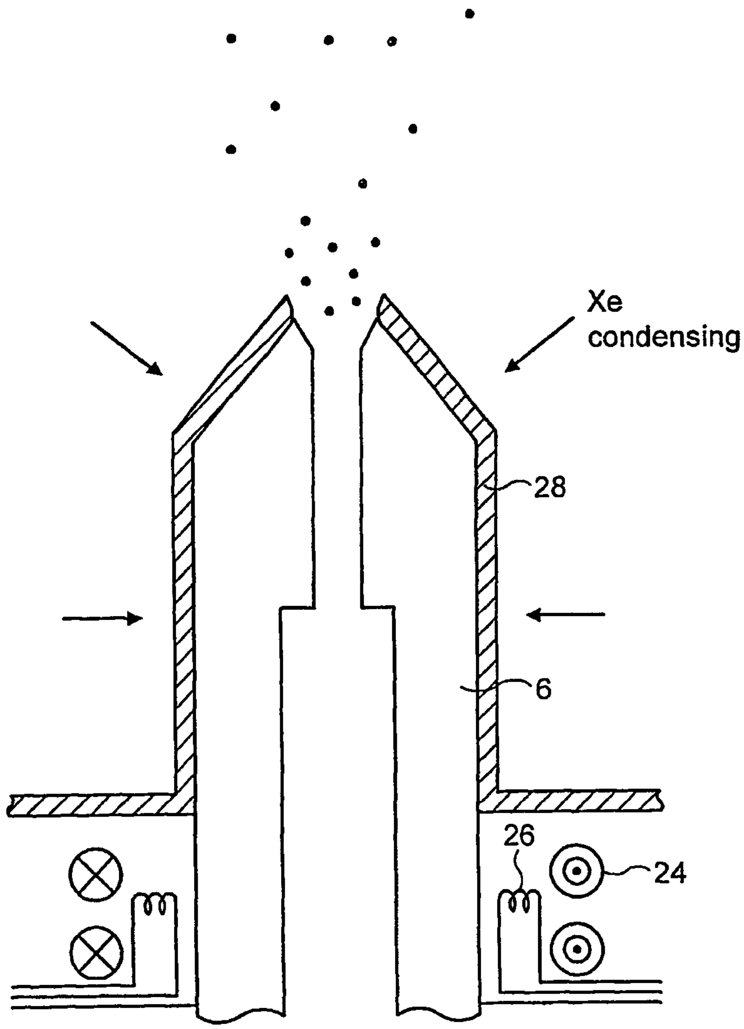

FIG. 3

SUBSTITUTE SHEET (RULE 26)

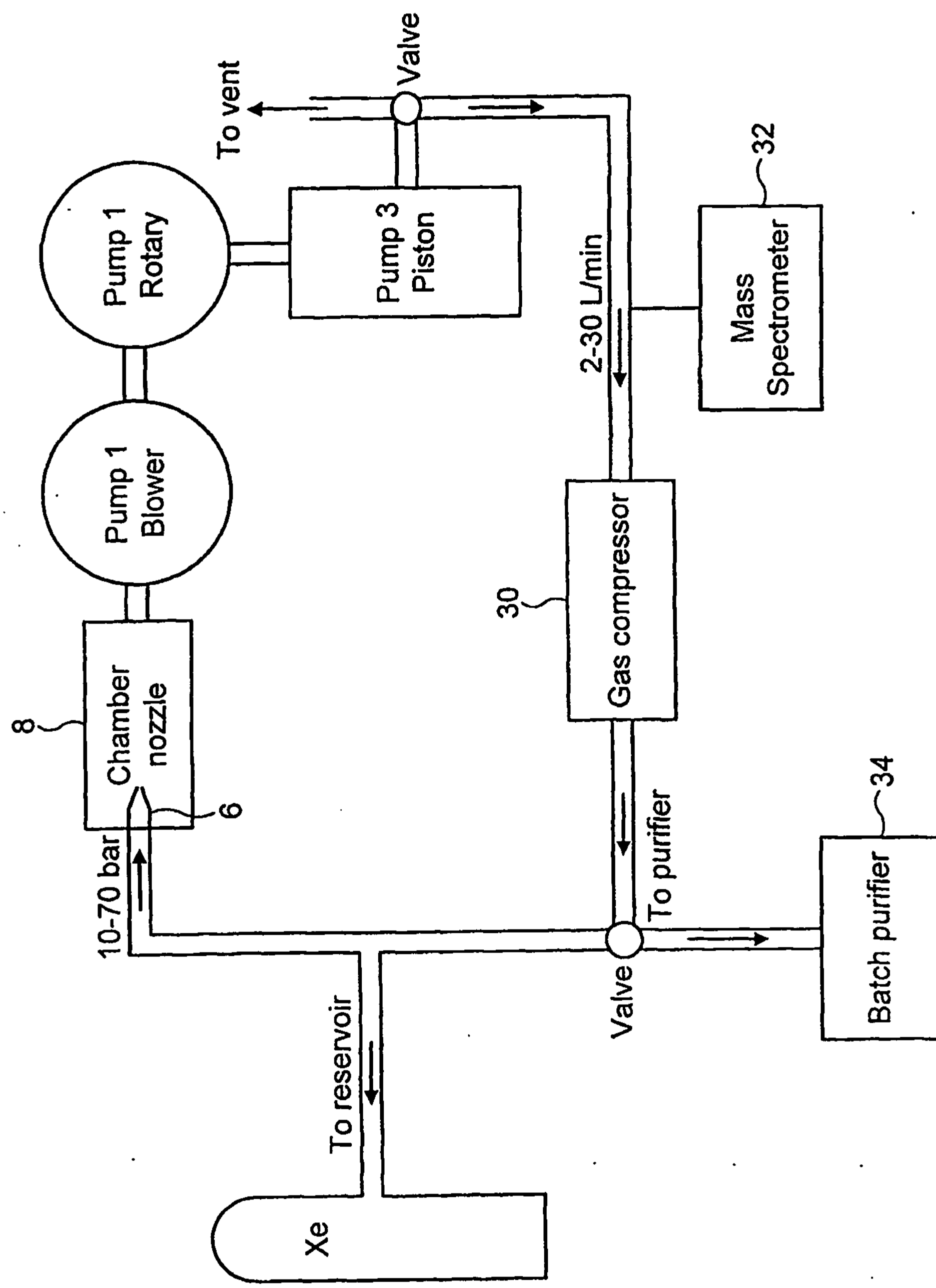
To vent
Valve
Pump 1
Rotary
Pump 3
Piston
2-30 L/min
32
Mass
Spectrometer
Pump 1
Blower
30
Gas compressor
8
Chamber
nozzle
6
10-70 bar
To purifier
34
Batch purifier
Valve
To reservoir
Xe

FIG. 4

INTERNATIONAL SEARCH REPORT

International Application No
PCT/GB 01/03871

A. CLASSIFICATION OF SUBJECT MATTER
IPC 7 H05G2/00

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 7 H05G

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

INSPEC, PAJ, WPI Data, EPO-Internal

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	EP 0 858 249 A (HITACHI LTD) 12 August 1998 (1998-08-12)	16
A	column 7; figure 1	1

X	WO 99 51356 A (ADVANCED ENERGY SYST) 14 October 1999 (1999-10-14)	16
A	page 18, line 17 - line 21; figure 1 page 6, line 26 -page 7, line 14	1

A	RYMELL L ET AL: "Liquid-jet target laser-plasma sources for EUV and X-ray lithography" MICROELECTRONIC ENGINEERING, ELSEVIER PUBLISHERS BV., AMSTERDAM, NL, vol. 46, no. 1-4, May 1999 (1999-05), pages 453-455, XP004170761 ISSN: 0167-9317 the whole document	1

☐ Further documents are listed in the continuation of box C.

☒ Patent family members are listed in annex.

° Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier document but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
29 October 2001	07.01.02

Name and mailing address of the ISA	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Tx. 31 651 epo nl, Fax: (+31-70) 340-3016	Oestreich, S

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INTERNATIONAL SEARCH REPORT

Box I Observations where certain claims were found unsearchable (Continuation of item 1 of first sheet)

This International Search Report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons:

1. ☐ Claims Nos.:
because they relate to subject matter not required to be searched by this Authority, namely:

2. ☐ Claims Nos.:
because they relate to parts of the International Application that do not comply with the prescribed requirements to such an extent that no meaningful International Search can be carried out, specifically:

3. ☐ Claims Nos.:
because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a).

Box II Observations where unity of invention is lacking (Continuation of item 2 of first sheet)

This International Searching Authority found multiple inventions in this international application, as follows:

see additional sheet

1. ☐ As all required additional search fees were timely paid by the applicant, this International Search Report covers all searchable claims.

2. ☐ As all searchable claims could be searched without effort justifying an additional fee, this Authority did not invite payment of any additional fee.

3. ☐ As only some of the required additional search fees were timely paid by the applicant, this International Search Report covers only those claims for which fees were paid, specifically claims Nos.:

4. ☒ No required additional search fees were timely paid by the applicant. Consequently, this International Search Report is restricted to the invention first mentioned in the claims; it is covered by claims Nos.:

1-16

Remark on Protest

☐ The additional search fees were accompanied by the applicant's protest.

☐ No protest accompanied the payment of additional search fees.

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FURTHER INFORMATION CONTINUED FROM PCT/ISA/ 210

This International Searching Authority found multiple (groups of) inventions in this international application, as follows:

1. Claims: 1-16

   Increase power of EUV source by mounting laser close to nozzle.

2. Claim : 17

   EUV source, focusing laser by mounting laser or nozzle on translation stage.

3. Claims: 18-30

   EUV source with recirculation and cleaning of target gas.

4. Claims: 31-39

   EUV source with temperature controlled nozzle.

INTERNA

Information on patent family members

Intern... ...al Application No
PCT/GB 01/03871

Patent document cited in search report		Publication date	Patent family member(s)		Publication date
EP 0858249	A	12-08-1998	JP	10221499 A	21-08-1998
			AU	5273298 A	13-08-1998
			CA	2229170 A	07-08-1998
			TW	393662 B	11-06-2000
			US	5991360 A	23-11-1999
WO 9951356	A	14-10-1999	US	6105885 A	22-08-2000
			US	6065203 A	23-05-2000
			AU	3469999 A	25-10-1999
			EP	1068020 A	17-01-2001